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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188

1a. REPORT SECURITY CLASSIFICATION	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFOSR-87-0378	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION University College of Wales 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Department of Physics, Penglais, Aberystwyth, Dyfed SY23 3BZ, U.K.	7b ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION EOARD 8b. OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) 223/231 Old Marylebone Road, LONDON NW1 5TH, U.K.	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO | PROJECT NO | TASK NO | WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)

Amplitude and Phase Scintillation and Ionospheric Irregularities at Sub-Auroral Latitudes.

12. PERSONAL AUTHOR(S)

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13a. TYPE OF REPORT	13b TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Interim Scientific	FROM 87.9.30 TO 89.1.31	89.3.31	37

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Radio-wave scintillations, ionospheric irregularities, high-latitude ionosphere.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Intensity and phase scintillation has been studied by monitoring transmissions from NNSS satellites at Lerwick, a sub-auroral location in northern UK. Observations commenced in July 1987 and the first part of the present report concentrates on an analysis of scintillation occurrence morphology during the first ten months of the investigation. A discrete region of irregularities close to the boundary is implied from the observations while the absence of a significant geometrical enhancement about the geomagnetic field position suggests that the irregularities close to the boundary may have small axial ratios. The remainder of the report is concerned with a comparative study of the scintillation boundary for irregularities of sub-kilometre scale and the boundary of <30 m scale irregularities causing auroral backscatter of HF radar signals. In general the scintillation boundary was found to be some 7° to 8° polewards of that detected by the radar. In a reanalysis of the data a reconciliation could be made to get agreement in only about half of cases studied.

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CHAPTER 1

INTENSITY AND PHASE SCINTILLATION MORPHOLOGY

INTRODUCTION

Radio waves traversing an irregular ionospheric medium are subject to spatial modulations of phase which result in random fluctuations or scintillations of both amplitude and phase of the signal received at the ground. Study of the scintillations is of importance not only to applications involving use of the transionospheric propagation channel but also to an understanding of the processes responsible for the ionospheric irregularities.

In a previous report and elsewhere in the published literature, Kersley et al. (1987 and 1988)[1,2] have described scintillation observations in the auroral zone over northern Europe and discussed results of long-term studies of scintillation occurrence in that region. The current report concerns an extension of the project to investigate scintillations and ionospheric irregularities from a site at a sub-auroral latitude making observations in the vicinity of the ionospheric trough and the scintillation boundary.

Full details of the NNSS system, the experimental arrangement and the signal processing have been reported earlier[3] and will not be repeated here. The

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1. Kersley L., Pryse S.E. and Wheadon N.S. Radio-wave scintillations and ionospheric irregularities at high latitudes. Report AFOSR-85-0190, University College of Wales, May 1987.
2. Kersley L., Pryse S.E. and Wheadon N.S. Amplitude and phase scintillation at high latitudes over northern Europe. Radio Sci., 23, 320, 1988.
3. Kersley L. High-latitude scintillations using NNSS satellites. AGARD Conf. Proc., CP-382, 2.7-1, 1985.

experiment was deployed at Lerwick in the Shetland Islands, UK (60.1°N, 1.2°W) for this second phase of observations commencing in July 1987. To date measurements have been obtained from more than 13,500 satellite passes. The average pass duration is around 11 minutes, giving a total of some 450,000 data records, with each record containing S_4, σ_ϕ and other parameters characterising the scintillation during a 20 second element of satellite pass.

This report discusses the basic occurrence morphology for scintillations based on the first nine months of observations at Lerwick. The parameters considered have been S_4 for the 150 MHz signal characterising intensity scintillations and σ_ϕ for the differential phase fluctuations between the 150 MHz signal and the 400 MHz reference after detrending with a 0.2 Hz cut-off filter.

Before results are presented a brief description is given of previous work on sub-auroral scintillations in the vicinity of the boundary.

BACKGROUND

Early in the satellite era it was appreciated that there was a region of scintillation producing irregularities encompassing the auroral zone which often displayed a sharp equatorwards boundary[4]. Studies of this so-called scintillation boundary were carried

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4. Aarons J., Mullen J.P. and Basu S. The statistics of satellite scintillation at a sub-auroral latitude. J. Geophys. Res., 68, 3159, 1963.

out by several workers in both northern and southern hemispheres. The work involved basic occurrence morphology including diurnal behaviour, response to geomagnetic activity and relationship to or independence from the ionospheric trough (see for example references 5 to 14). Many of these early studies were however

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5. Beynon W.J.G. and Jones E.S.O. The scintillation of radio signals for the Discoverer 36 satellite. J. Atmos. Terr. Phys. 26, 1175, 1964.
6. Kaiser A.B. and Preddey G.F. Observations of transitions in satellite scintillation. J. Atmos. Terr. Phys., 30, 285, 1968.
7. Aarons J., Mullen J.P. and Whitney H.E. The scintillation boundary. J. Geophys. Res., 69, 1785, 1969.
8. Frihagen J. Satellite scintillation at high latitudes and its possible relation to precipitation of soft particles. J. Atmos. Terr. Phys., 31, 81, 1969.
9. Aarons J. The high latitude F-region irregularity structure during the October 30 to November 4, 1968, magnetic storm. Radio Sci., 5, 959, 1970.
10. Aarons J. and Allen R.S. Scintillation boundary during quiet and disturbed magnetic conditions. J. Geophys. Res., 76, 170, 1971.
11. Oksman J. and Tauriainen A. On annual movements of the scintillation boundary of satellite signals. J. Atmos. Terr. Phys., 33, 1727, 1971.
12. Stuart G.F. Characteristics of the abrupt scintillation boundary. J. Atmos. Terr. Phys., 34, 1455, 1972.
13. Kersley L., Jenkins D.B. and Edwards K.J. Relative movements of mid-latitude trough and scintillation boundary. Nature Phys. Sci., 239, 11, 1972.
14. Kersley L., van Eyken A.P. and Edwards K.J. Ionospheric mid-latitude trough and the abrupt scintillation boundary. Nature, 254, 312, 1975.

carried out using signals in the lower VHF range and the scintillation, if quantified, was described using simple forms of scintillation index based on depth of fading criteria.

Observations from Millstone Hill, USA, using NNSS satellites to determine S_4 at 150 MHz were reported by Wand and Evans (1975)[15]. They showed an equatorwards motion of the scintillation boundary in response to magnetic activity which was especially marked in the midnight sector in winter and in the early morning sector in summer. No strong correlation was found between scintillation boundary and trough position even for cases of an abrupt boundary in agreement with the European studies of Kersley et al. (1975)[14].

From quantitative measurements, using the Wideband satellite, in Alaska, Rino and Matthews (1980)[16] concluded that in the local midnight sector the boundary moved on average from 65° dip latitude at K=0 to 55° at K=7 while in the morning sector the corresponding latitudes were 70° and 60° respectively.

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15. Wand R.H. and Evans J.V. Morphology of ionospheric scintillation in the auroral zone. I.E.S.75, NTIS CSCL 04/1 N75-30714, NRL, Washington D.C., 1975.
16. Rino C.L. and Matthews S.J. On the morphology of auroral zone radio wave scintillation. J. Geophys. Res., 85, 4139, 1980.

The most recent published work on the boundary is that of Hajkowicz (1982)[17], for 150 MHz NNSS transmissions but not quantified in terms of the S_4 scintillation parameter. He demonstrated that the response to magnetic activity in the southern hemisphere was essentially similar to that in the north.

RESULTS

Scintillation morphology is described in terms of the percentage occurrence above specified threshold levels of S_4 and σ_ϕ for 150 MHz intensity and differential phase respectively. Direct comparison is thus possible between the current observations and those obtained earlier at the auroral site[18,1]. As in these earlier reports the irregularity height has been taken to be 350 km.

The variation of intensity scintillation occurrence as a function of geomagnetic latitude for several S_4 thresholds can be seen from the examples of Fig. 1.1 for an equinoctial month (March) and a winter month (January). Data for satellite passes within ± 20° longitude were used. The general levels of occurrence are much less than observed at the auroral location, though at first sight enhancements towards the northern horizon and in the centre of the scan appear similar to the earlier

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17. Hajkowicz L.A. *Equatorwards limits of the southern scintillation oval.* J. Atmos. Terr. Phys., 44, 539, 1982.
18. Kersley L., Pryse S.E. and Wheadon N.S. Radio-wave scintillations and *ionospheric irregularities at high latitudes.* Report AFOSR-85-0190, University College of Wales, May 1986.

PERCENTAGE OCCURRENCE GREATER
THAN A SPECIFIED S4 LEVEL
LERWICK-JANUARY-1988

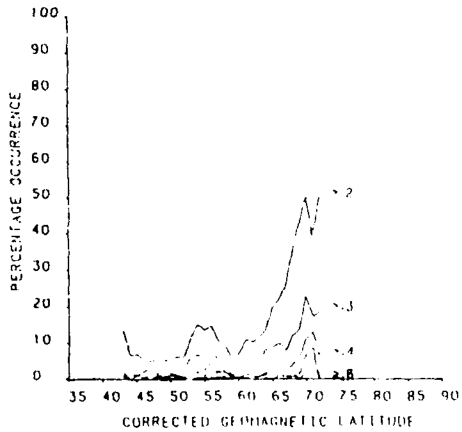


Figure 1.1a

PERCENTAGE OCCURRENCE GREATER
THAN A SPECIFIED S4 LEVEL
LERWICK-MARCH-1988

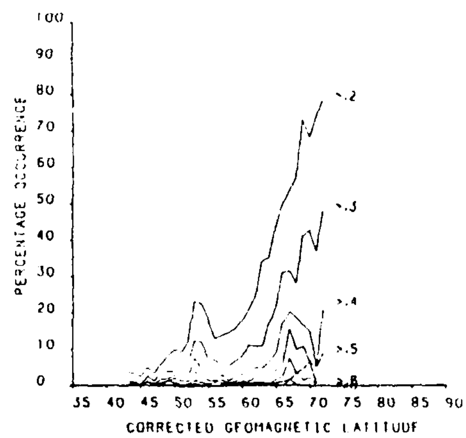


Figure 1.1b

PERCENTAGE OCCURRENCE GREATER
THAN A SPECIFIED S4 LEVEL
LERWICK-APRIL-1988

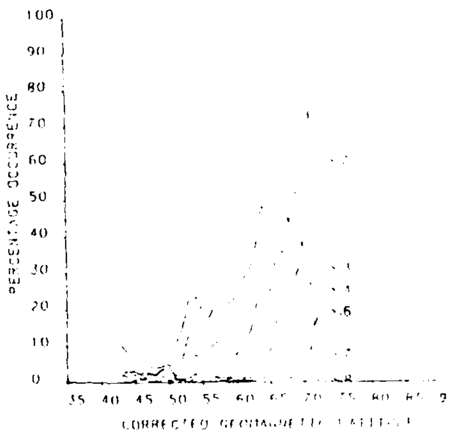


Figure 1.1c

results. Closer examination, however, reveals that the central enhancement cannot be identified with the geometrical effect which causes increased scintillation as the ray path becomes aligned with the geomagnetic field or the Briggs-Parkin angle minimises. The latitude for field alignment of the ray path in the F-region is 57.8^{0} CGM for observations from Lerwick, however it can be seen that the observed central peak maximises several degrees to the. south. The higher levels of occurrence at equinox than in winter can also be noted. Indeed, in Fig. 1.1c for April even greater occurrence levels are found at central latitudes than in March and it can be seen that the anticipated geometrical enhancement about the field aligned latitude is beginning to play a role, at least for lower S_4 thresholds, though the other maximum to the south is still present. The interpretation of these observations in terms of an irregularity distribution will be discussed later.

The basic features of scintillation occurrence can be seen from the series of graphs follows which have been obtained using the first ten months of observational data In each case care must be taken to note the contour levels which, though specified on each graph, do vary from plot to plot. Care must also be exercised in the interpretation of the figures close to the edges of the plots where edge effects in the contouring routines may result in spurious detail or contours which do not map accurately from edge to edge. However, in general, the database is so extensive that the plots give a reliable guide to scintillation occurrence exceeding specified threshold levels of the S_4 and σ_φ indices for intensity and phase respectively.

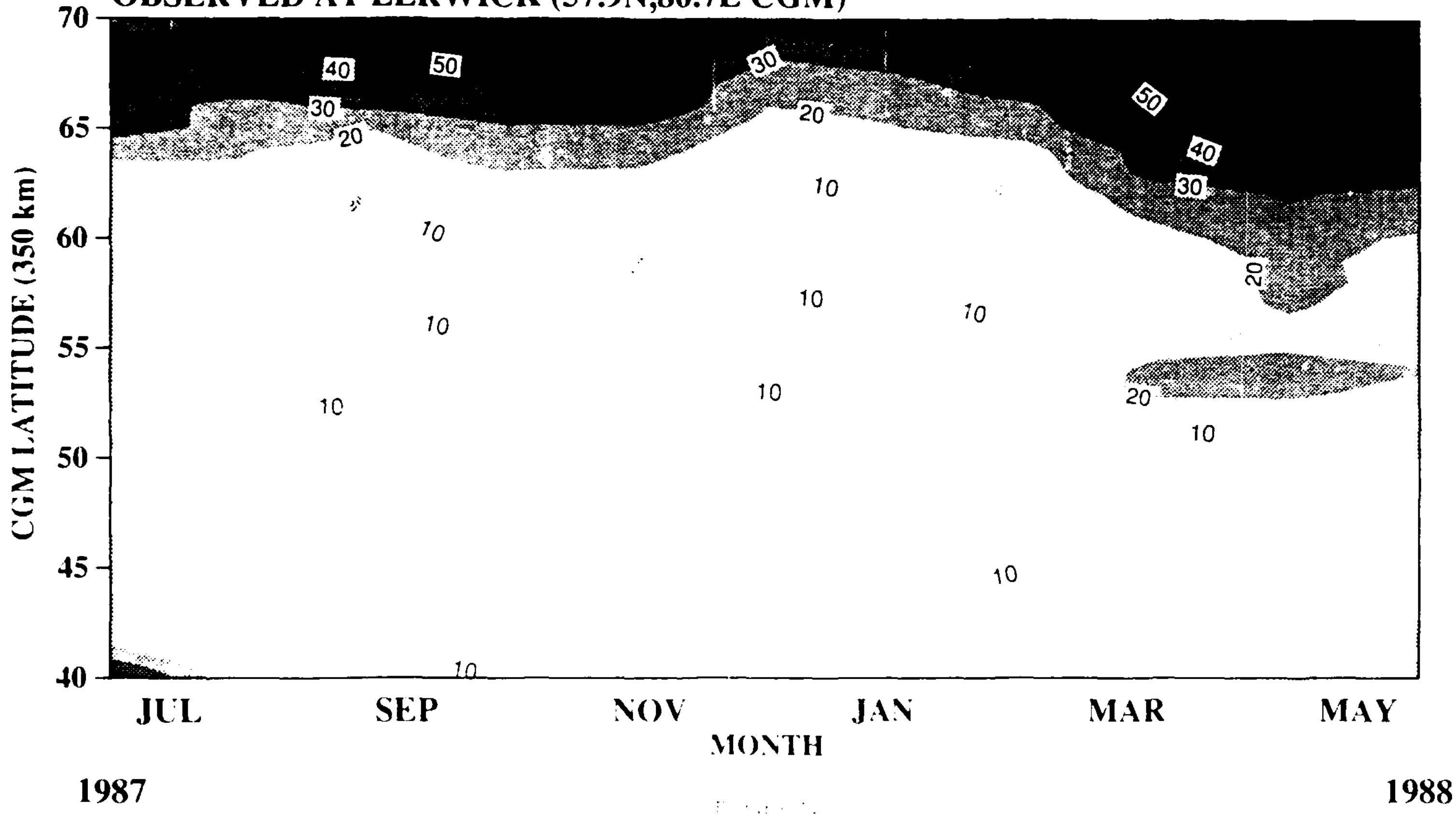
A discussion on choice of thresholds and in particular on the use of a value of 25^{0} for σ_φ for the conditions appropriate to the present experiment was included in an earlier report[1].

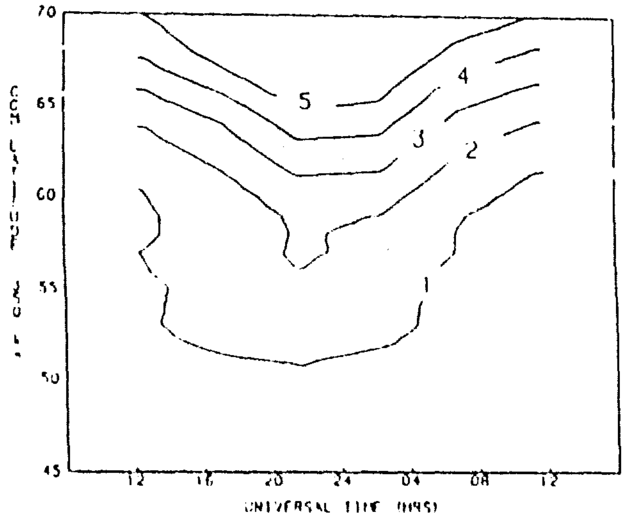
An overview of scintillation occurrence at this sub-auroral location can be gained from Fig. 1.2. This shows contours of percentage occurrence of intensity scintillation with $S_4 > 0.2$ as a function of corrected geomagnetic latitude by month for the entire data set under consideration here. A polewards movement of the contours in the winter months can be seen adding confirmation to the seasonal trends found in the earlier observations at Kiruna. The greatest occurrence was towards the end of the observing period shown here, though discussion on whether this is a purely seasonal effect or that it contains a contribution from the greatly increased solar activity in 1988 must await the analysis of subsequent observations.

The diurnal variations of scintillation occurrence for the three seasonal groupings are shown in Figs. 1.3 and 1.4, for intensity scintillation with $S_4 > 0.2$ and phase scintillation with $\sigma_\varphi > 25^{\circ}$, respectively. A clear boundary with equatorwards motion in the night sector can be seen in all of the plots, though differences in both latitudinal extension and duration are apparent in the different seasons. Figs 1.3 and 1.4 contain data for all states of magnetic activity. In an attempt to show effects of magnetic activity on average behaviour of scintillation occurrence in this sub-auroral region, the data were grouped into three ranges corresponding to low Kp (0, 1), medium Kp (2, 3) and high Kp ($\geq$4). The corresponding diurnal variations of intensity scintillation for the three seasons are shown in Figs. 1.5 to 1.7.

For the earlier auroral zone observations made at Kiruna it was possible to infer that sheet-like irregularities played an important contribution in the scintillation occurrence. This was done by plotting the observations as a function of geographic latitude and longitude and comparing the occurrence distributions with those anticipated from model studies incorporating irregularities with differing anisotropies.

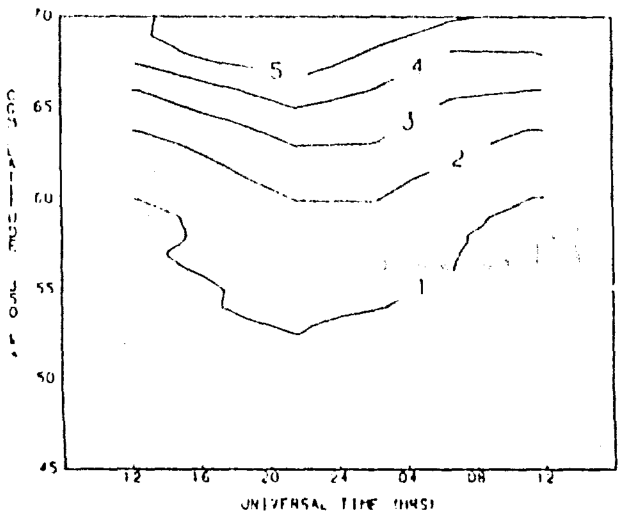
MONTHLY PERCENTAGE SCINTILLATION OCCURRENCE FOR SΦ0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)





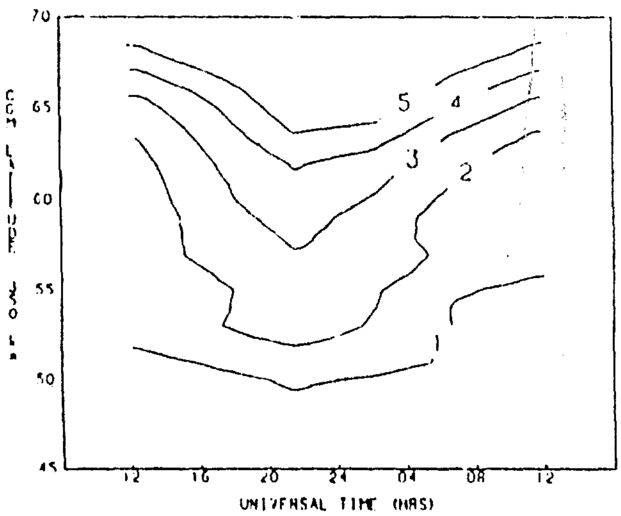
CONTOUR LEVELS: 1=15% 2=25% 3=35% 4=45% 5=55%

DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
AUTUMN 87   ALL KP



CONTOUR LEVELS: 1=15% 2=25% 3=35% 4=45% 5=55%

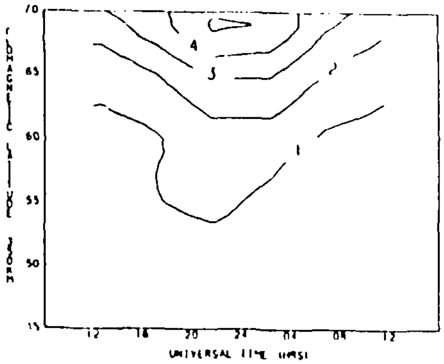
DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
WINTER 87/88 ALL KP



CONTOUR LEVELS: 1=15% 2=25% 3=35% 4=45% 5=55%

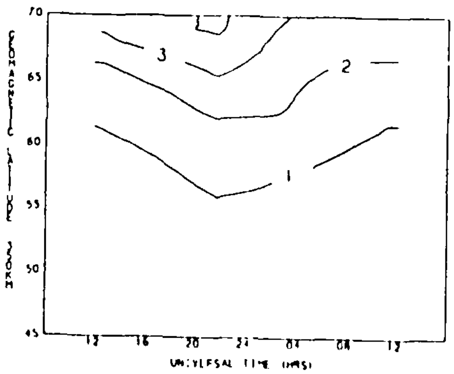
DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
SPRING   88 ALL KP

Figure 1.3



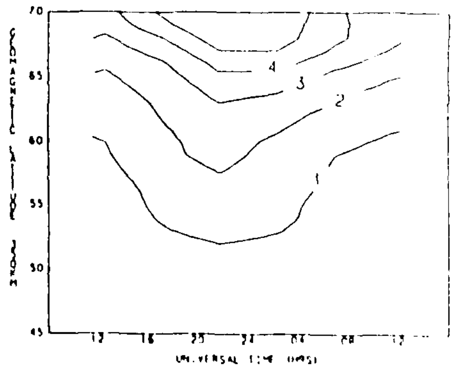
CONTOUR LEVELS: 1=10% 2=20% 3=30% 4=40% 5=50%

DIURNAL VARIATION IN RMS PHASE >25 DEGREES
OBSERVED AT LERWICK
AUTUMN 87 ALL KP



CONTOUR LEVELS: 1=10% 2=20% 3=30% 4=40% 5=50%

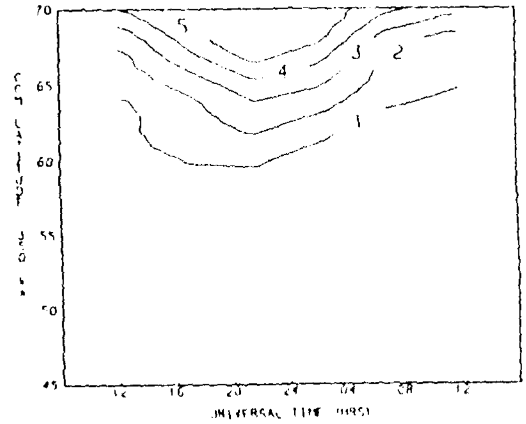
DIURNAL VARIATION IN RMS PHASE >25 DEGREES
OBSERVED AT LERWICK
WINTER 87/88 ALL KP



CONTOUR LEVELS: 1=10% 2=20% 3=30% 4=40% 5=50%

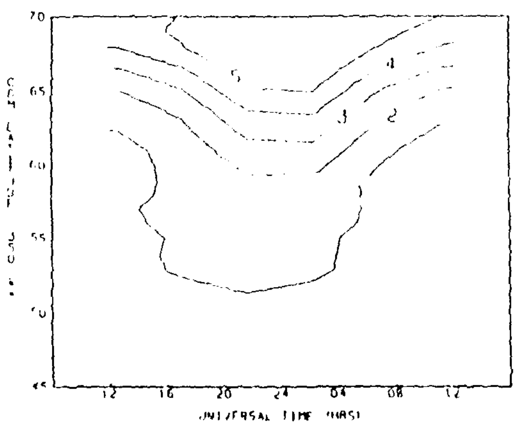
DIURNAL VARIATION IN RMS PHASE >25 DEGREES
OBSERVED AT LERWICK
SPRING 88 ALL KP

Figure 1.4



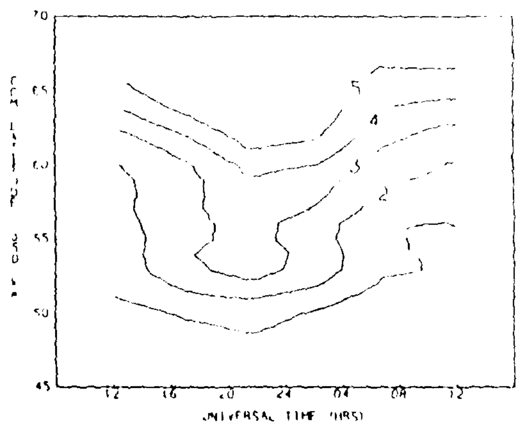
CONTOUR LEVELS: 1=15% 2=25% 3=35% 4=45% 5=55%

DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
AUTUMN 87 LOW KP



CONTOUR LEVELS: 1=15% 2=25% 3=35% 4=45% 5=55%

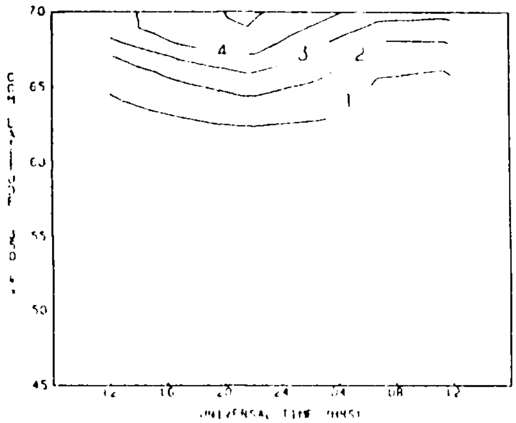
DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
AUTUMN 87 MED KP



CONTOUR LEVELS: 1=15% 2=25% 3=35% 4=45% 5=55%

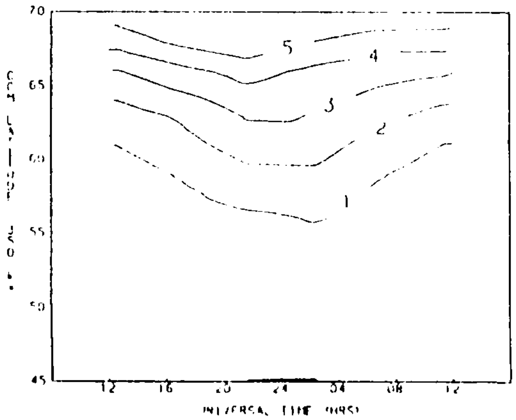
DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
AUTUMN 87 HI KP

Figure 1.5



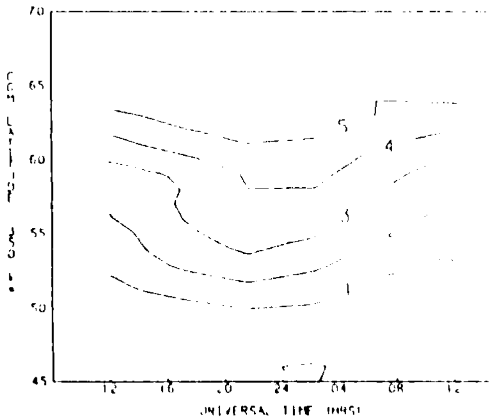
CONTOUR LEVELS: 1-15% 2-25% 3-35% 4-45% 5-55%

DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
WINTER 87/88 LOW KP



CONTOUR LEVELS: 1-15% 2-25% 3-35% 4-45% 5-55%

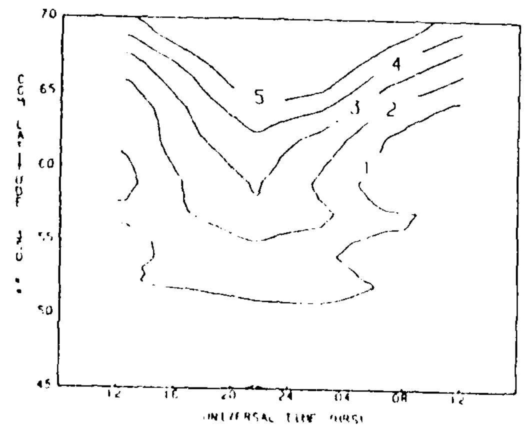
DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
WINTER 87/88 MED KP



CONTOUR LEVELS: 1-15% 2-25% 3-35% 4-45% 5-55%

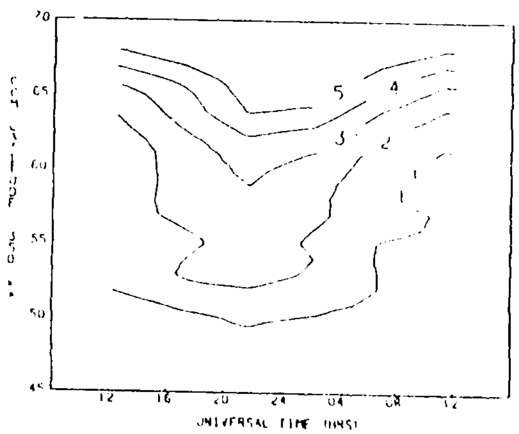
DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
WINTER 87/88 HI KP

Figure 1.6



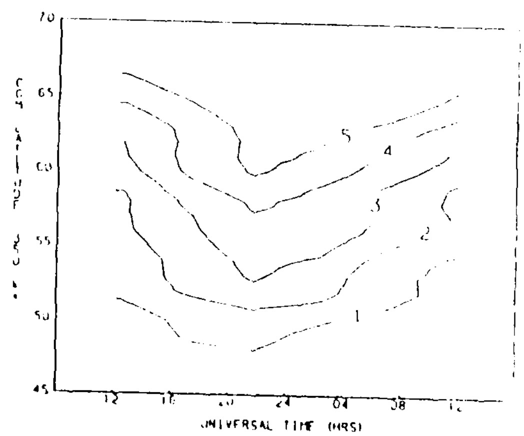
CONTOUR LEVELS: 1-15% 2-25% 3-35% 4-45% 5-55%

DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
SPRING 88 LOW KP



CONTOUR LEVELS: 1-15% 2 25% 3-35% 4 45% 5 55%

DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
SPRING 88 MED KP



CONTOUR LEVELS: 1-15% 2-25% 3-35% 4-45% 5 55%

DIURNAL VARIATION OF SCINTILLATION S4>0.2
OBSERVED AT LERWICK (57.9N,80.7E CGM)
SPRING 88 HI KP

Figure 1.7

The saddle-like nature of the observed conditions as opposed to closed loops around the position of the field line was taken to indicate the role of sheet-like irregularities as opposed to field-aligned rods.

Plots of intensity scintillation occurrence (S_4 > 0.2) at Lerwick as a function of geographic latitude and longitude are shown for autumn 1987 and spring 1988 in Fig. 1.8. It can be seen that, apart from horizon effects in the southern corners, the contours essentially follow the L-shells.

A general model of scintillation, based on phase screen theory, in which the irregularity size distribution is characterised by a power law spectral density function, has been developed by Rino (1979)[19]. The use of this model to investigate the effects of observational geometry and irregularity anisotropy in the earlier auroral zone observations at Kiruna has been discussed by Kersley et al. (1987 and 1988)[1,2]. Similar techniques have been applied to the current sub-auroral observations. Fig. 1.9 shows plots appropriate to Lerwick of the geometrical multiplying factor, normalised to an overhead value of unity, in the modelled S_4 index as a function of azimuth and elevation for four different irregularity anisotropies. These comprise field-aligned rods with axial ratios 3:1 and 8:1 and L-shell confined sheets with ratios 3:3:1 and 8:8:1. Comparison of Fig. 1.9 with the observations of Fig. 1.8 shows little similarity in the general form of the plots regardless of the irregularity model chosen.

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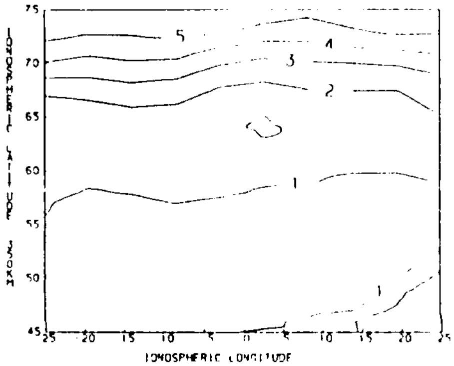
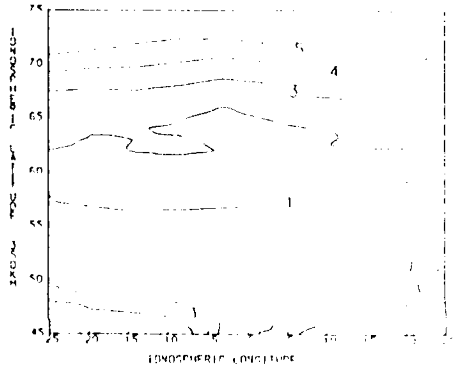
19. Rino C.L. A power law phase screen model for ionospheric scintillation. 1. Weak Scatter. Radio Sci., 14, 1135, 1979.



CONTOUR LEVELS: 1-15% 2-25% 3-35% 4-45% 5-55%

OCCURRENCE OF SA>0.2
OBSERVED AT LERWICK (60.1N,1.5W)
AUTUMN 1987



CONTOUR LEVELS: 1-15% 2-25% 3-35% 4-45% 5-55%

OCCURRENCE OF SA>0.2
OBSERVED AT LERWICK (60.1N,1.5W)
SPRING 1988

Figure 1.8

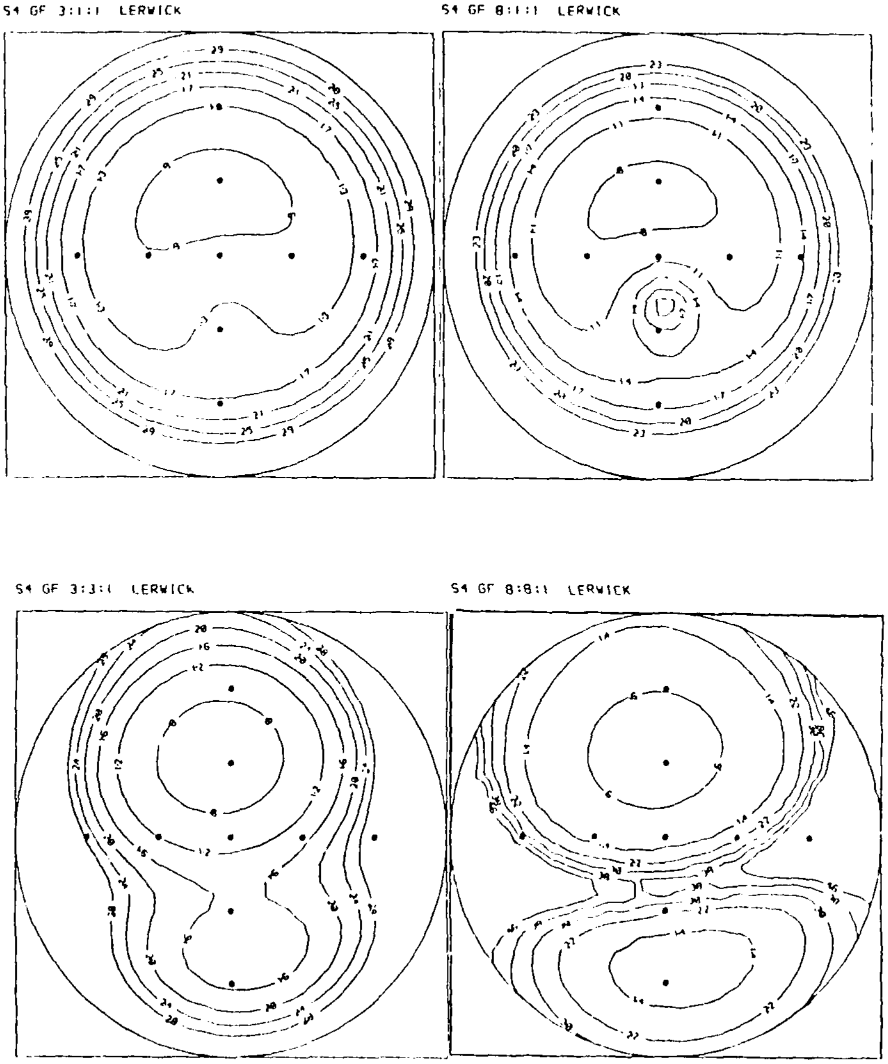

S4 GF 3:1:1 LERWICK
S4 GF 8:1:1 LERWICK
S4 GF 3:3:1 LERWICK
S4 GF 8:8:1 LERWICK

Figure 1.9

DISCUSSION AND CONCLUSIONS

Interpretation of the scintillation measurements in terms of irregularity behaviour must be treated with caution due to the geometrical influences on the observations. However it is possible to draw certain limited conclusions from the restricted data set of the initial observations at Lerwick presented here. The most important of these relates to the apparent absence of a marked field-aligned or L-shell confined enhancement in much of the data, as evidenced for example in Figs. 1.1 and 1.8. It is clear from the diurnal plots that for much of the time the irregularity region does not take in the field-aligned latitude, the boundary being well polewards of the station. However, even when the boundary is far enough south it would appear that a field-aligned enhancement is present in only a minority of the data. Further analysis is required to verify this point, but the initial results would appear to suggest that the axial ratios of the irregularities is not large near the boundary. For example, the model studies of Fig. 1.9 show that the enhancement in S_4 is only 20% for rod-like irregularities with axial ratio 3:1. It is apparent from the data that there is an additional enhancement close to the edge of the boundary generally at a latitude a few degrees equatorwards of the field-aligned latitude. This observation appears to indicate a discrete region of irregularities close to the boundary. It is possible that this region is linked to electron density gradients equatorwards of the trough minimum. Indeed, in studies using observations of the BE-B satellite Jenkins (1971)[20] showed evidence for the scintillation boundary south of the trough minimum. Investigations using HF radars, which will be reviewed in the next chapter, provide further evidence for two discrete regions of irregularities.

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20. Jenkins D.B. Some beacon satellite studies of the ionosphere. M.Sc. Thesis, University of Wales, 1971.

The results presented here provide the first overview of the initial scintillation observations from the sub-auroral location. It is clear that several new features of interest have been raised which will be subject to further study as the investigation proceeds.

CHAPTER 2

BOUNDARIES FOR SCINTILLATION AND AURORAL BACKSCATTER

INTRODUCTION

Irregularities in the F-layer cause scintillation on transionospheric propagating signals. The effect of irregularities is also manifest as direct scatter of HF signals using obliquely radiating antennas. Indeed for such systems under certain conditions, strong backscattered signals are observed which appear at a constant apparent range over a wide frequency band.

Using an oblique-incidence, swept-frequency sounder, Möller (1964)[1] observed high-frequency backscatter from field-aligned irregularity sheets or 'HF curtains'. He detected two latitudinal regions for such curtains, one at the equatorwards edge of the auroral oval and the other on the poleward wall of the ionospheric trough. Möller and Tauriainen (1975)[2] reported HF backscatter and scintillations occurring along the northern wall of the trough. Subsequently Oksman and Tauriainen (1978)[3] found HF curtains on both sides of the trough minimum, with essentially similar

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1. Möller H.G. Backscatter observations at Lindau-Harz with variable frequency directed to the auroral zone. Arctic Communications, B. Landmark, ed., Agardograph 78, pp 177-188, The MacMillan Co., N.Y., 1964.
2. Möller H.G. and Tauriainen A. Observations of intense irregularities in the polar F-region by HF backscatter and satellite scintillation measurements. J. Atmos. Terr. Phys., 37, 161, 1975.
3. Oksman J. and Tauriainen A. On the relative location of the TEC trough and HF backscatter curtains. COSPAR Proc., 12, 1978.

results being reported by Turunen and Oksman (1979)[4] and Oksman et al. (1979)[5]. More recently, Nekrasov et al. (1982)[6] found two bands of spread F, one centred around 68° and the other near 60° geomagnetic latitude.

On an oblique incidence backscatter ionogram the slant F or 'auroral' trace is a manifestation of direct backscatter from field-aligned irregularities. Möller (1974)[7] has discussed the form of such traces and has shown that for a radar location at a sufficiently low latitude where it is possible to achieve ray orthogonality with the geomagnetic field at F-region altitudes, the ionogram trace appears as a constant range extension to higher frequencies. In this circumstance the backscatter occurs from irregularities with scale size transverse to the magnetic field of half the radar wavelength, which for an HF radar would be typically about 10m.

For some months during 1987/8 an HF radar system was operated from the south of England radiating essentially northwards. The resulting oblique-incidence wide-sweep

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4. Turunen T. and Oksman J. On the relative location of the plasmapause and the HF backscatter curtains. J. Atmos. Terr. Phys., 41, 345, 1979.
5. Oksman J., Möller H.G. and Greenwald R. Comparisons between strong HF backscatter and VHF radar aurora. Radio Sci., 14, 1121, 1979.
6. Nekrasov B.Y., Shirochkov A.V. and Shumilov I.A. Investigation of the irregular structure of the polar ionosphere using oblique incidence soundings. J. Atmos. Terr. Phys., 44, 769, 1982.
7. Möller H.G. Backscatter results from Lindau-II. The movement of curtains of intense irregularities in the polar F-layer. J. Atmos. Terr. Phys., 36, 1487, 1974.

backscatter ionograms show auroral trace features from which in *principle* it is possible to estimate the range and thus location of the equatorwards edge of the HF backscatter curtain for 10m scale irregularities.

Scintillations of VHF signals are a manifestation of irregularities of scale size in the sub-kilometre regime. The HF radar and the scintillation techniques thus provide complementary methods for observing irregularities in two different scale size regimes. In particular simultaneous observations of the equatorwards edge of the HF backscatter curtain and the scintillation boundary not only may provide evidence on irregularity behaviour, but also may provide information on the usefulness of satellite transmissions to the interpretation of HF propagation conditions. It was to these ends that a study was made of the backscatter ionograms and the scintillation data base in a comparison of boundary locations.

ANALYSIS OF HF BACKSCATTER IONOGRAMS

The data base of backscatter ionograms, covering the period 23 December 1987 to 26 August 1988, was examined for examples showing an auroral trace. The time delay of the lower edge of the auroral backscatter trace, expressed as a one-way group path was determined in each case. The ionograms for the summer months were more complicated than those obtained earlier, so that in some instances identification of an 'auroral' trace was difficult. In particular, it is possible that the results for May have been contaminated by a component associated with sporadic-E rather than an F-layer scatter mechanism. In the other summer months care was taken to eliminate this component from the data set.

In calculating the latitude of the irregularities causing backscatter the following assumptions were made:

a) It was assumed that the ionospheric scattering came from a height of 300 km.

b) Although most of the observations were for radar directions slightly to the east or to the west of true north, it was assumed that all observations were in the true north direction and that the radio waves had travelled along straight-line paths.

c) The receiver and transmitter were assumed to be at 51.4° N latitude.

ANALYSIS OF SCINTILLATION DATA

The S_4 scintillation index, obtained from the 150MHz transmission, was plotted for all NNSS passes at times close to those when auroral backscatter was observed. Passes showing a scintillation boundary, using an S_4 threshold of 0.2, were identified and the time and latitude of the boundary noted. For the initial analysis the boundary was taken to occur at the highest latitude at which the S_4 index fell below 0.2 when coming from the north.

RESULTS

1. Initial Analysis

a) HF auroral backscatter boundary.

A plot of boundary latitude as a function of universal time for all the HF data available is shown in Fig. 2.1. The average latitude from 345 data points is 60.4^{o} N with a standard deviation of 3.1^{o}. The corresponding plot excluding the data for May which could be contaminated by non-auroral returns shows (Fig. 2.2) that for this data set of 216 points, the average latitude is 61.1^{o} N with a standard deviation of 3.0^{o}. Changing the assumed height of the back scatter irregularities to 350 km and still excluding the May data yielded Fig. 2.3. Here the average latitude was found to be 60.9^{o} N with a standard deviation of 3.1^{o}

BOUNDARY FROM HF RADAR DATA

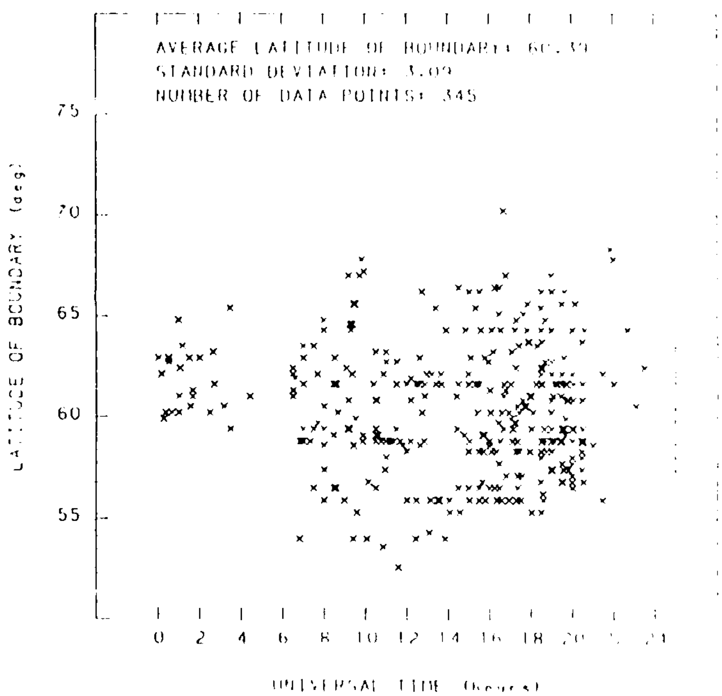

Figure 2.1

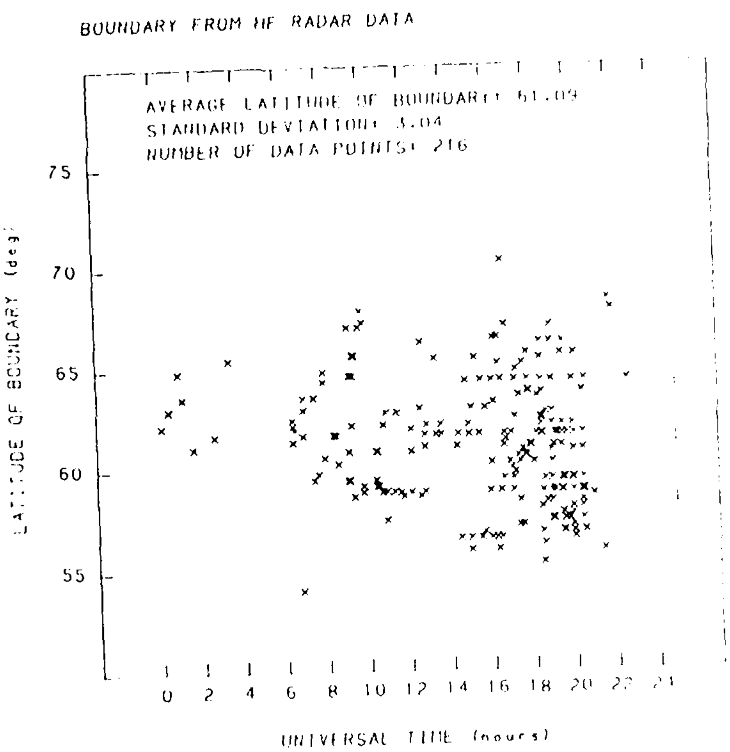
BOUNDARY FROM HF RADAR DATA
AVERAGE LATITUDE OF BOUNDARY: 61.09
STANDARD DEVIATION: 3.04
NUMBER OF DATA POINTS: 216
LATITUDE OF BOUNDARY (deg)
75
70
65
60
55
0
2
4
6
8
10
12
14
16
18
20
22
24
UNIVERSAL TIME (hours)

Figure 2.2

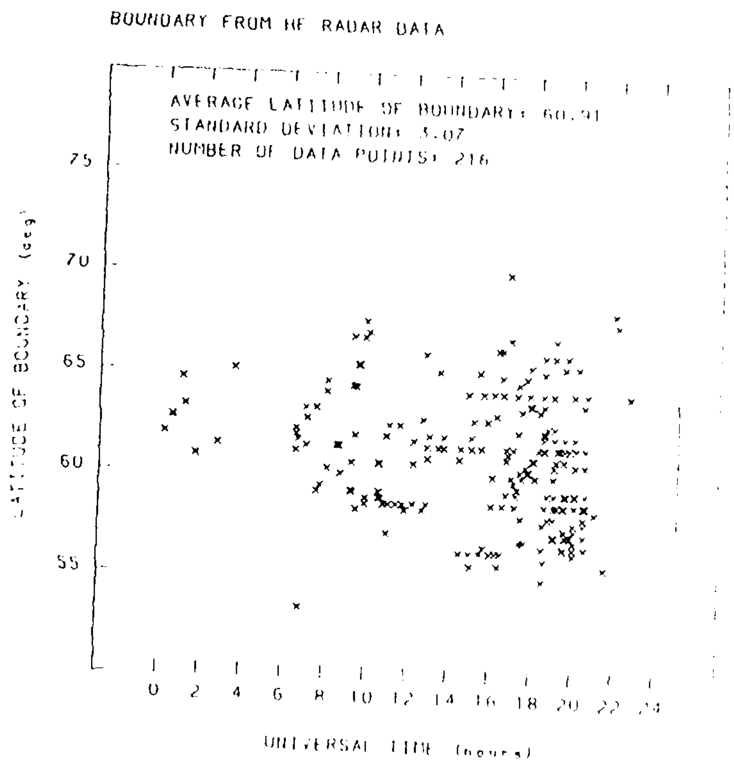
BOUNDARY FROM HF RADAR DATA
AVERAGE LATITUDE OF BOUNDARY: 60.91
STANDARD DEVIATION: 3.07
NUMBER OF DATA POINTS: 216
75
70
65
60
55
LATITUDE OF BOUNDARY (deg)
0
2
4
6
8
10
12
14
16
18
20
22
24
UNIVERSAL TIME (hours)

Figure 2.3

b) Scintillation boundary

The latitude of the scintillation boundary as a function of universal time is plotted in Fig. 2.4 using all 87 data points. The average position was found to be 68.9^{o} N with a standard deviation of 3.7^{o}. Corresponding plots for low, medium and high ranges of K_p proved inconclusive, although it should be noted that each grouping comprised a statistically small number of points.

c) Comparisons of boundaries

(i) The results already presented show that there is a significant difference of about 8^{o} between the equatorwards boundary for HF auroral backscatter and that for scintillation, with the latter being found at higher latitudes. A scatter plot giving corresponding positions of the two boundaries observed simultaneously is shown in Fig. 2.5. For this, from the scintillation boundaries found within ± 1 hour of an HF ionogram showing an auroral trace the one closest in time has been plotted. The computer program used for this procedure results in some scintillation boundary positions being used for two or more adjacent ionograms so that the total data set comprises 107 points. The mean boundary positions are found to be separated by about 8^{o} latitude while the standard deviations are only around 3^{o}. A similar result can be seen in Fig. 2.6 where the time separation has been reduced to ± 30 min. With a restriction in time between the boundaries of only ± 15 min the data set is reduced to 40 points (Fig. 2.7). However, the scintillation boundary still remains on average 7^{o} higher in latitude than that for the radar observations, a difference much greater than the standard deviation of about 3^{o}.

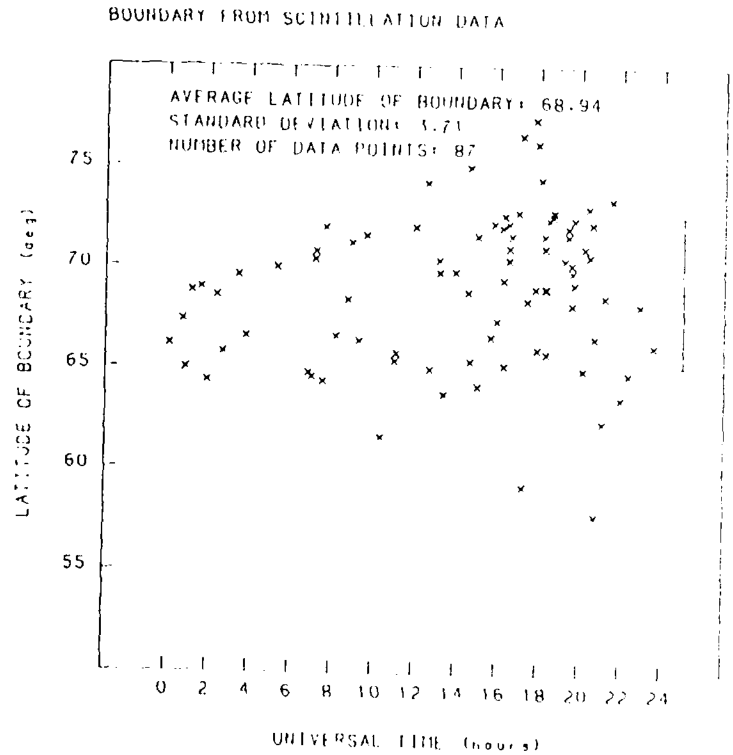
BOUNDARY FROM SCINTILLATION DATA
AVERAGE LATITUDE OF BOUNDARY: 68.94
STANDARD DEVIATION: 3.71
NUMBER OF DATA POINTS: 87
LATITUDE OF BOUNDARY (deg)
75
70
65
60
55
0 2 4 6 8 10 12 14 16 18 20 22 24
UNIVERSAL TIME (hours)

Figure 2.4

HF RADAR BOUNDARY VS SCINTILLATION BOUNDARY

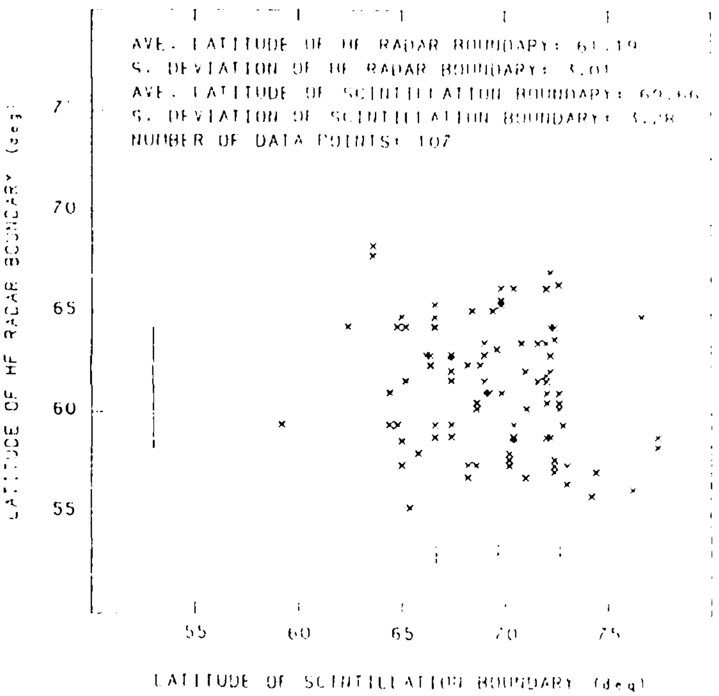

Figure 2.5

HF RADAR BOUNDARY VS SCINTILLATION BOUNDARY

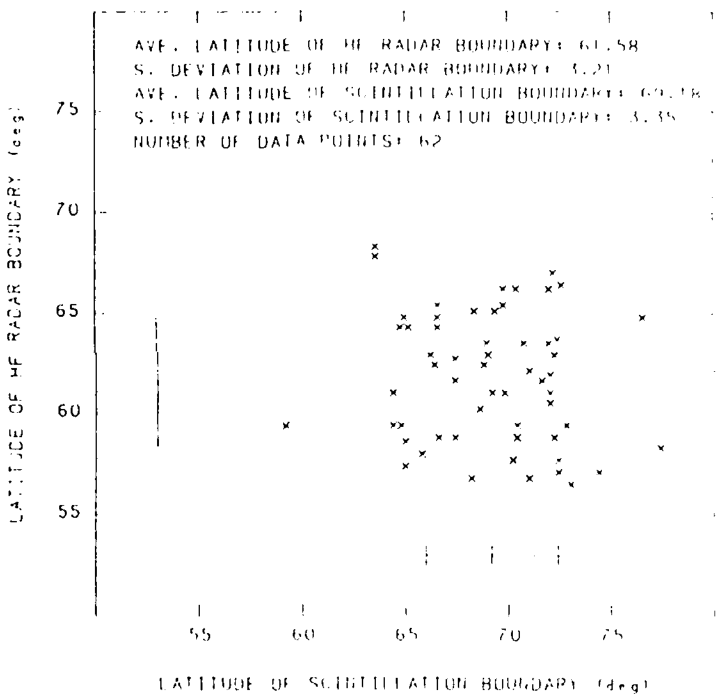

Figure 2.6

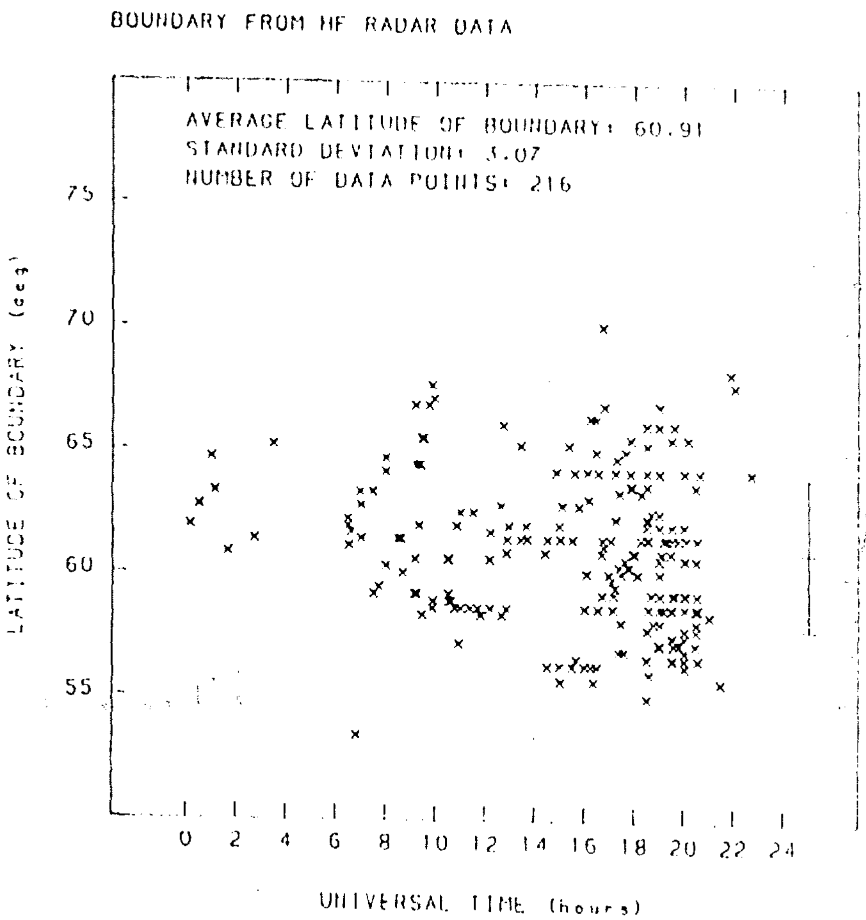
BOUNDARY FROM HF RADAR DATA
AVERAGE LATITUDE OF BOUNDARY: 60.91
STANDARD DEVIATION: 3.07
NUMBER OF DATA POINTS: 216
LATITUDE OF BOUNDARY (deg)
75
70
65
60
55
0
2
4
6
8
10
12
14
16
18
20
22
24
UNIVERSAL TIME (hours)

Figure 2.3

(ii) The boundary positions within ± 1 hour were also compared directly with a scintillation boundary being paired with only one HF ionogram, that being the one closest in time. This resulted in 59 pairs of boundaries. For each pair the difference between the latitudes of the scintillation boundary and HF radar boundary was determined, and plotted as a function of time (Fig. 2.8). This again indicates a difference of about 8° latitude between the two boundaries with the scintillation boundary being lower than the HF radar boundary on only two occasions.

2. Modified Analysis

In the initial analysis described above the scintillation boundary position was defined in terms of the highest latitude at which S_4 fell below the 0.2 threshold when coming from the north. It is clear from the results that there is a difference of some 7° or 8° in latitude between the position of this boundary and that observed by the HF radar. It is also of significance that the latitude of the boundary for <30 m scales was found to be close to the region where a geometrical enhancement in scintillation arising from the field-alignment of the irregularities would be expected. Thus it would be anticipated that sub-kilometre irregularities at a latitude close to where the HF boundary was observed would be more likely to be manifest as scintillation. However, it would appear from the results presented that only irregularities of the smaller scale were present in sufficient magnitude to be detected by the techniques. In the above analysis an arbitrary definition of scintillation boundary, based on a threshold crossing from the north, had been used. In an attempt to verify the results the analysis was repeated now defining the scintillation boundary to occur at the lowest latitude at which the S_4 index increased above 0.2

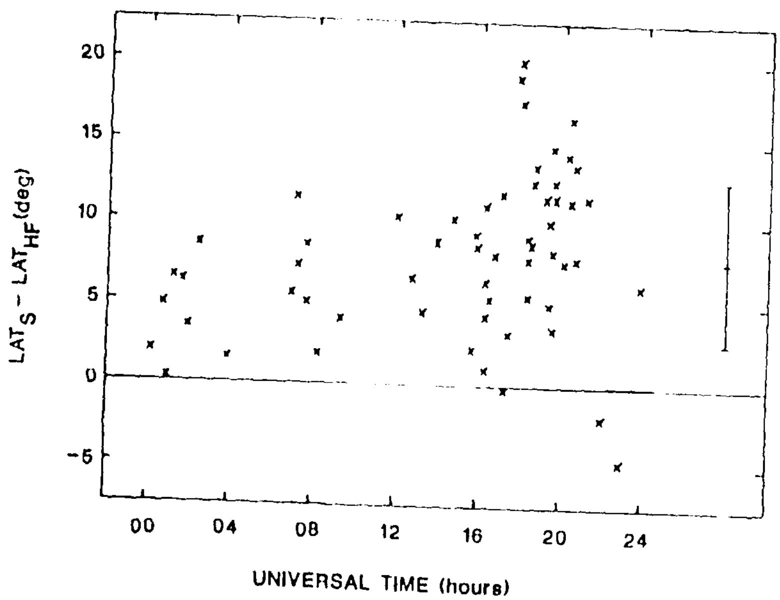
20
15
10
5
0
-5
$LAT_S - LAT_{HF}$ (deg)
00
04
08
12
16
20
24
UNIVERSAL TIME (hours)

Figure 2.8

when coming from the south. In 29 of the 59 cases a different boundary location was found using this criterion. Fig. 2.9 shows these cases with the latitude difference between this newly-defined scintillation boundary and the HF radar boundary plotted as a function of time of day. It can now be seen that for the sub-set of the data there is little significant difference between the boundary positions. For the mean difference the scintillation boundary occurs about 3° equatorwards of that determined by the backscatter technique, nevertheless the error bars encompass the position of coincidence. However, it should be noted that for the remaining half of the data (30 out of 59 observations) the scintillation boundary was found significantly polewards of the HF backscatter boundary.

CONCLUSIONS

The equatorwards boundary for <30 m scale irregularities observed by the HF backscatter technique has been found to occur around 60° geographic latitude. In about half of the cases where there was a close proximity in time between the satellite pass and the radar observations it was found that there was little significant difference between the positions of the two boundaries. The results suggested that the scintillation boundary was marginally equatorwards of that for the auroral backscatter. That is, the longer-lived larger scale (sub-kilometre) irregularities responsible for VHF scintillation were found to be at slightly lower latitudes than the shorter term small scale (<30 m) structures causing auroral backscatter. The observation of the scintillation boundary in this region may be consistent with the results on scintillation morphology given in Chapter 1 of this report where there were clear indications of a discrete region of irregularities to the south of Lerwick which was detached from the irregularity continuum at auroral latitudes.

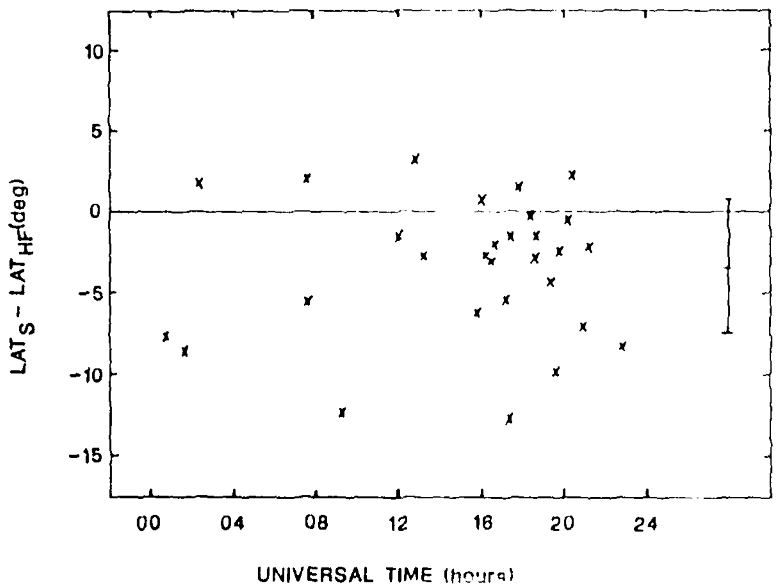
10
5
0
-5
-10
-15
$LAT_S - LAT_{HF}$(deg)
00
04
08
12
16
20
24
UNIVERSAL TIME (hours)

Figure 2.9

To our knowledge, the only other study of scintillation and HF backscatter was that reported by Möller and Tauriainen (1975)[2]. Their observations were for the auroral zone but separated in longitude by some 20°. The results for 65 cases studied indicated a median difference in latitude for the two boundaries close to zero with a quartile range of less than ± 1.5°. It can also be noted that the median latitudinal width of the regions of scintillation studied was only some 4°. However, there are indications (see for example Fig. 2 of the paper) that the observations were contaminated significantly by geometrical effects, the work having been carried out before the enhancements due to observational and irregularity geometry, which are of particular importance in the auroral zone, were quantified. Thus, while good agreement was found between the irregularity positions located by the two techniques we believe that this result should be treated with caution because of the particular circumstances of the observations, even though it provides confirmation for the coincidence found in about half the cases studied in the present work.

It is important to note that in the remaining half of the current data set the boundary latitudes were separated by 7° to 8°, so that in these cases the scintillation technique does not provide a reliable indicator of possible effects on the radar. In an explanation of these examples further study would need to be done of radar performance and of signal ray paths since effects of ionisation gradients may have been causing signal returns which masked backscatter at a greater range and were themselves interpreted as arising from irregularities.